

# The Effects of Radiation on 1/f Noise in Complementary (npn + pnp) SiGe HBTs

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**Abstract**— We present the first study of the effects of radiation on low-frequency noise in a novel complementary (npn + pnp) SiGe HBT BiCMOS technology. In order to manipulate the physical noise sources in these complementary SiGe HBTs, 63.3 MeV protons were used to generate additional (potentially noise-sensitive) traps states. The base currents of both the npn and pnp SiGe HBTs degrade with increasing proton fluence, as expected, although in general more strongly for the npn transistors than for the pnp transistors, particularly in inverse mode. For the pnp SiGe HBTs, irradiation has almost no effect on the 1/f noise to proton fluences as high as  $5.0 \times 10^{13} \text{ p/cm}^2$ , while the npn SiGe HBTs show substantial radiation-induced excess noise. In addition, unlike for the pnp devices, which maintain an  $I_B^2$  bias dependence, the 1/f noise of the post-irradiated npn SiGe HBTs change to a near-linear dependence on  $I_B$  at low base currents following radiation, suggesting a fundamental difference in the noise physics between the two types of devices.

## I. INTRODUCTION

High-speed complementary (npn + pnp) bipolar transistor technology has long been recognized for its many advantages in high-performance analog IC design, particularly for low voltage circuits and push-pull architectures. In such complementary technologies, however, maintaining adequate performance in the pnp transistor is very difficult, partially compromising the utility of complementary analog technologies. It is generally recognized that bandgap engineering using silicon-germanium (SiGe) alloys has a very favorable impact on key analog figures-of-merit such as gain, frequency response, output conductance,  $\beta V_A$  product, and noise [1], and many such SiGe HBT technologies are in wide-spread use today. Exclusively, however, such SiGe technologies are based around npn SiGe HBT configurations. SiGe HBTs using pnp's are known to be more challenging in their design and optimization [1], and the successful monolithic integration of SiGe npn's and SiGe pnp's to form a complementary SiGe analog technology has proven exceptionally challenging to achieve. Recently, however, a novel complementary SiGe HBT BiCMOS technology on SOI has in fact been reported [2], opening the way to a new level of performance in analog IC design.

Low-frequency noise in transistors usually exhibits a 1/f-like spectrum, sets the lower limit on the detectable signal level, can

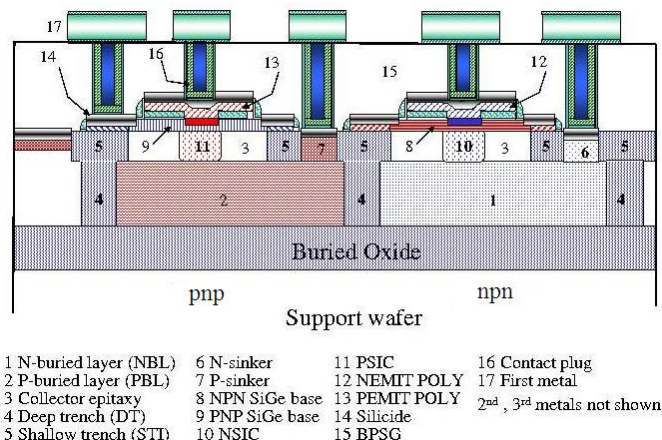


Fig. 1. Schematic device cross-section of novel complementary SiGe HBT technology.

be up-converted to higher frequencies corrupting spectra purity (phase noise), and hence is a key design constraint in nearly all analog ICs and systems. Radiation experiments have proven to be very useful in probing the physical noise sources in npn SiGe HBTs [3][4]. In this work we present the first radiation results of complementary SiGe HBTs, and use radiation to probe the differences in underlying physics of 1/f noise between npn and pnp SiGe HBTs.

## II. DEVICE TECHNOLOGY AND EXPERIMENT

This novel complementary SiGe HBT BiCMOS technology (Figure 1) was fabricated by Texas Instruments, and involves dual depositions of SiGe epitaxy (boron doped for the npn, and phosphorus doped for the pnp), shallow and deep trench isolation, polysilicon emitter contacts with thin, interfacial oxide layers (more process details can be found in [2]). Both npn and pnp SiGe HBTs, as well as the Si CMOS devices, were integrated on SOI material. Due to the need of achieving comparable current gain between the npn and pnp transistors, a controlled emitter interfacial oxide (between the single crystal Si emitter and the heavily doped polysilicon contact) was used to independently adjust the npn and pnp transistors. Because such interfacial oxides are known to affect low-frequency noise, we have also compared two complementary SiGe HBT processes fabricated identically, except with differing interfacial oxide thicknesses on the npn SiGe HBT (the pnp emitter process was held fixed).

Transistors of varying geometries were measured. The width of both the npn and pnp devices was fixed at  $0.4 \mu\text{m}$ , while the length was varied from  $0.8 \mu\text{m}$  to  $6.4 \mu\text{m}$ . Measured pre-radiation cutoff frequencies ( $f_T$ ) of the complementary SiGe HBTs are both 19 GHz, with Early voltages ( $V_A$ ) of the npn and pnp tran-

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sistors of 150V and 100V, respectively [2]. The samples were irradiated with 63.3 MeV protons at the Crocker Nuclear Laboratory at the University of California at Davis. At proton fluences of  $1.0 \times 10^{12}$  and  $5.0 \times 10^{13}$  p/cm<sup>2</sup>, the measured equivalent gamma dose was approximately 135 and 6,759 krad(Si), respectively. An automatic noise measurement was developed to measure the noise power spectral density of the devices. The block diagram of the system is shown in figure 6. Wire-wound potentiometers  $R_{PB}$  and  $R_{PC}$  are controlled by a computer through two stepping motors [5]. Since the control system between the stepping motors and the computer is isolated by relays, the 60Hz fluctuations from the ac power source do not degrade the measured data. An Agilent 35670A Dynamic Signal Analyzer was used to measure the voltage power spectrum densities  $S_{VB}$  and  $S_{VC}$  from resistors  $R_S$  and  $R_L$ , which are series-connected with the base and the collector terminals, respectively.

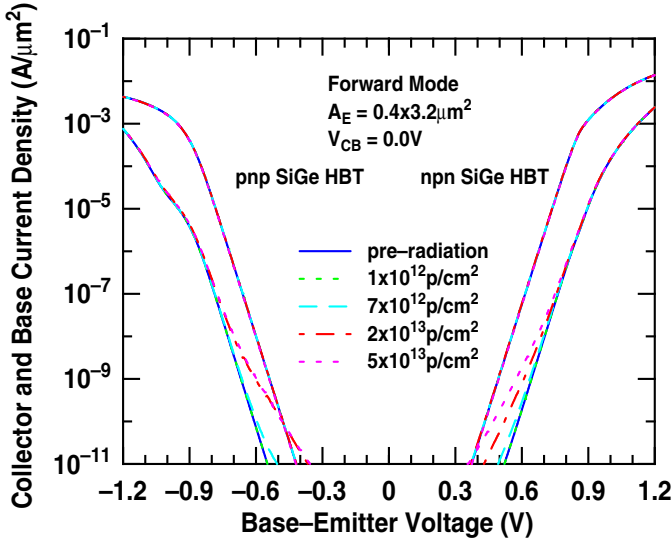


Fig. 2. Gummel characteristics for pre- and post-irradiated complementary SiGe HBTs.

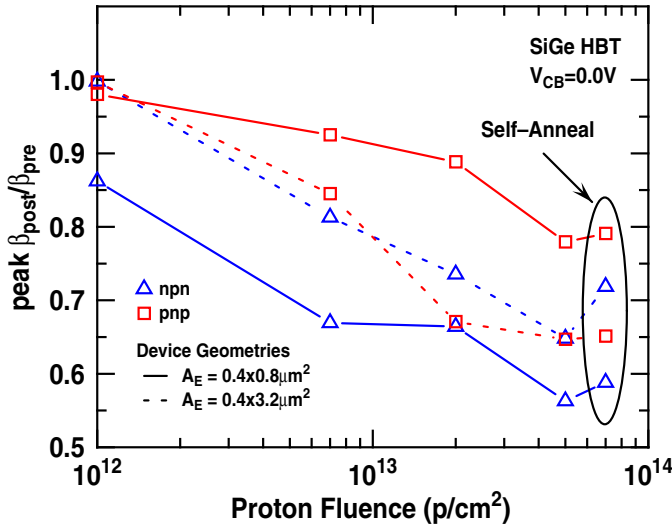


Fig. 3. Current gain degradation for the complementary SiGe HBTs.

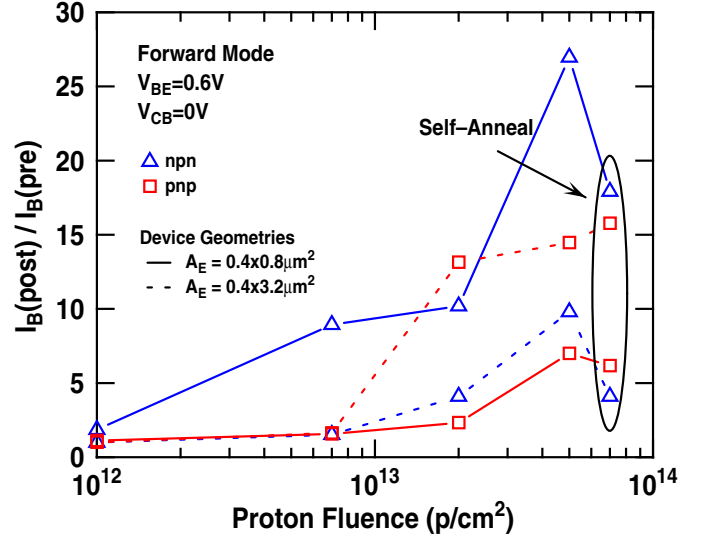


Fig. 4. Base current degradation as a function of fluence in forward mode for the complementary SiGe HBTs.

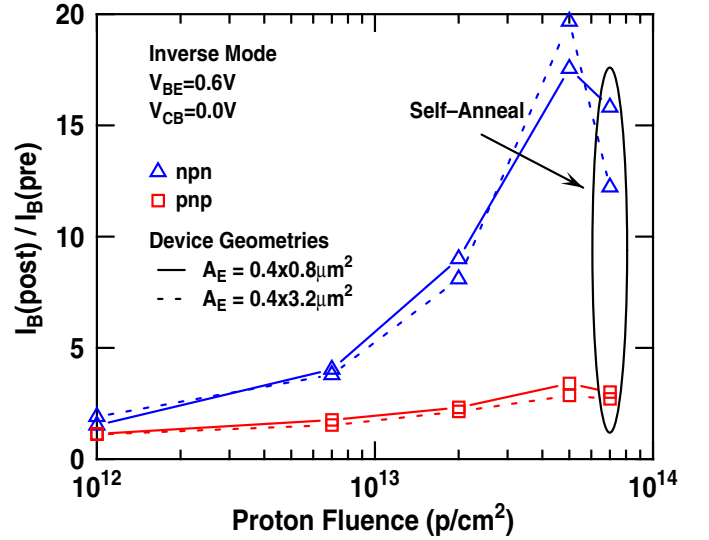


Fig. 5. Base current degradation as a function of fluence in inverse mode for the complementary SiGe HBTs.

### III. RESULTS

Figure 2 shows the radiation response of the Gummel characteristics for both device types as a function of proton fluence. With increasing fluence, the non-ideal base current component increases, as expected, indicating that radiation-induced G/R traps are being added to the device as the proton fluence increases. Figures 3-5 show the current gain, and normalized base current change for both npn and pnp SiGe HBTs in both forward and inverse mode (emitter-base terminals swapped) as a function of proton fluence. Interestingly, the pnp SiGe HBTs generally show significantly better radiation tolerance than the npn SiGe HBTs, particularly in inverse mode, although clearly there is a strong dependence on device geometry. This suggests that the damage thresholds between the two device types are fundamentally different, despite the near-identical processing associated with the sensitive damage regions (i.e., the emitter-base

spacer oxide and the shallow trench edge). We also consistently observed significant spontaneous self-annealing at room temperature over the span of about 6 weeks.

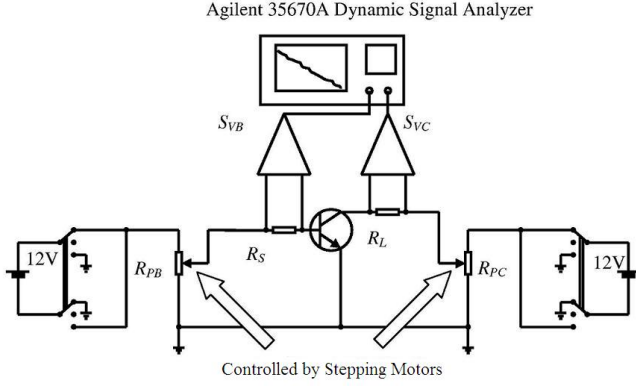


Fig. 6. Schematic block diagram for the automatic noise measurement system.

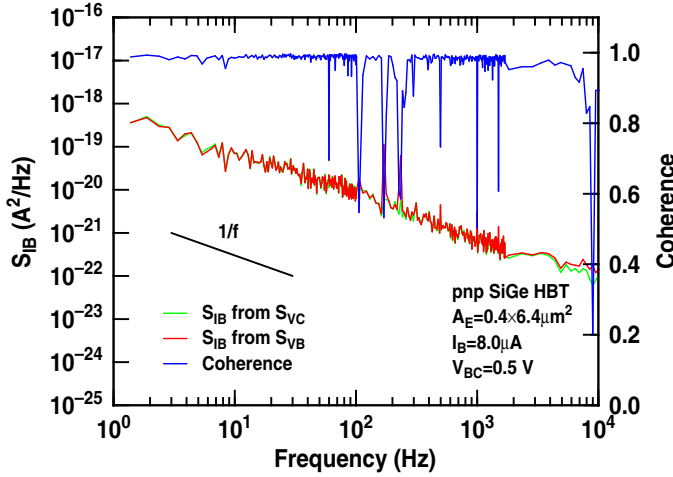


Fig. 7. Extracted power spectra density and coherence measurement data.

For the pre-irradiated devices, the noise is  $1/f$  in shape and is generally similar to that observed in conventional Si BJTs [6], with the equivalent current noise source  $S_{IB}$  exhibiting an  $I_B^2$  dependence and inverse proportionality to emitter area  $A_E$ . The npn transistor noise is consistently smaller than that of the pnp's.

The base and collector terminal noise coherence between  $S_{VB}$  and  $S_{VC}$  is close to unity (Figure 7), which means that only one noise source is dominant inside the device [7]. From Figure 7, we can see that  $S_{IB}$  extracted from the two channels almost overlap each other, confirming that  $S_{IB}$  is the dominant noise source in both the npn and pnp SiGe HBTs. We scanned the noise in the devices from  $I_B = 0.1 \mu\text{A}$  to  $I_B = 8 \mu\text{A}$ . Over this base current range all of the spectra show clear  $1/f$  dependences and increase with base current  $I_B$ . To avoid small size effects [8], we focus our studies here on the largest device with  $A_E = 0.4 \times 6.4 \mu\text{m}^2$ .

Interestingly, the post-irradiated devices demonstrate a strongly dissimilar behavior between the npn and pnp SiGe HBTs. For the pnp transistors, the  $1/f$  noise remains nearly unchanged up to proton fluence of  $5.0 \times 10^{13} \text{p/cm}^2$ . For npn transistors, however, the magnitude of the  $1/f$  noise significantly in-

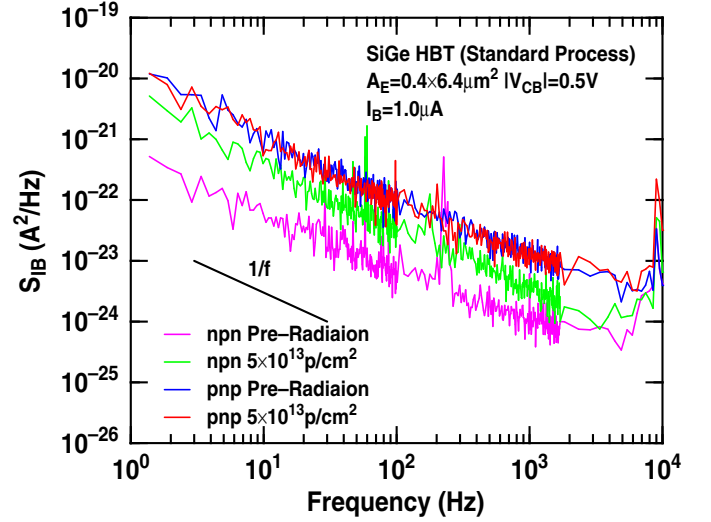


Fig. 8. Comparison of the pre-radiation and the post-radiation  $S_{IB}$  spectra for both npn and pnp SiGe HBTs.

creases after irradiation. This difference in noise response to radiation occurs in spite of the similar response between the npn and pnp device current-voltage characteristics at the same proton fluence. Even more surprising, in the npn SiGe HBTs, at low base currents ( $I_B < 0.8 \mu\text{A}$ ) the quadratic dependence of the noise changes to a near linear dependence on base current after radiation exposure, remaining as an  $I_B^2$  dependence at higher bias levels. No such behavior is seen in the pnp transistors.

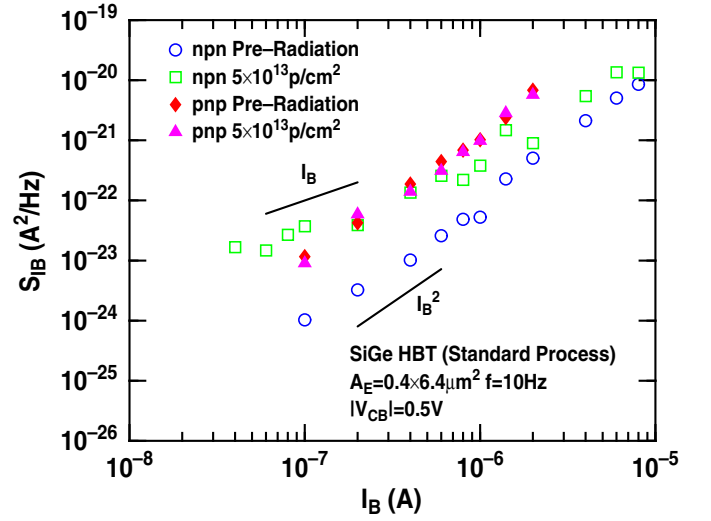


Fig. 9. Effects of irradiation on the bias dependence of the noise at 10Hz for both npn and pnp SiGe HBTs.

$S_{IB}$  at 10 Hz comparison for the devices with the different npn interfacial oxide are shown in Figure 10. As expected, the npn SiGe HBT with the thicker interfacial oxide has a larger  $1/f$  noise magnitude. Note, however, that the npn device with the thicker interfacial oxide also exhibits the same anomalous  $I_B$  dependence at low base currents as seen in the standard process, suggesting that the observed differences in noise physics between the npn and pnp SiGe HBTs is fundamental, and not dependent on differences in the emitter interface preparation.

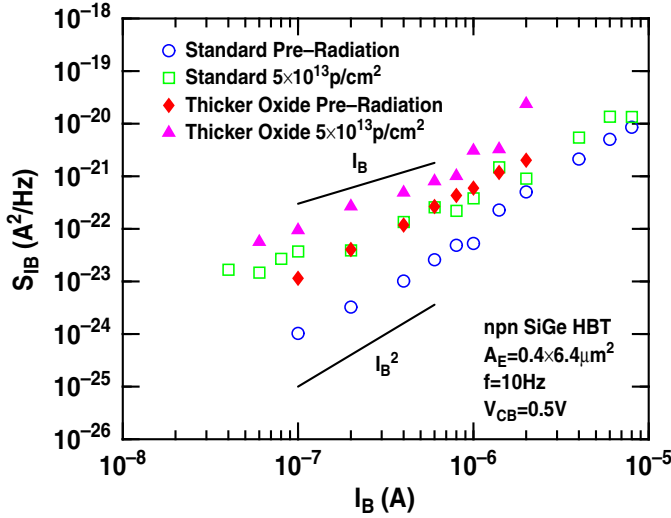


Fig. 10. Effects of irradiation on the bias dependence of the noise at 10Hz in npn SiGe HBTs with different interfacial oxide thicknesses.

#### IV. THEORY AND DISCUSSION

A noise model which predicts an  $I_B^2$  dependence of  $S_{IB}$  is the "transparency fluctuation model," proposed by Kleinpenning [9][10][11]. This model assumes that the thermal noise from the interfacial oxide can modulate the hole barrier height. Hence, the oxide generates the so-called "transparency fluctuation," or tunneling probability fluctuation, through the oxide. Thus, the current passing through the emitter is modulated by the transparency fluctuation, which induces  $1/f$  noise. According to this theory, the noise source can be expressed as:

$$\frac{S_{IB}}{I_B^2} = \frac{m^* q k T \tan(\xi) L^3}{3 \pi \epsilon' V_0 \hbar^2 A_E f} \left[ \frac{1}{1 + v_{ox} \left( \frac{1}{v_m} + \frac{W_m}{D_m} + \frac{W_p}{D_p} \right)} \right]^2 \quad (1)$$

where,  $m^*$  is the carrier effective mass,  $q$  is the electron charge,  $L$  is the oxide thickness,  $W_p$  and  $W_m$  are the width of the poly emitter and monosilicon layers respectively,  $D_p$  and  $D_m$  are the carrier diffusion constants of the poly emitter and monosilicon layers, respectively,  $v_m$  and  $v_{ox}$  are the recombination velocities of carriers at the metal contact surface and in the interfacial oxide, respectively,  $V_0$  is the oxide barrier height, and  $\epsilon'$  is the dielectric constant of the oxide. Therefore, the transparency fluctuation model predicts that the  $1/f$  noise is inversely proportional to device area  $A_E$  and has a cubic functional dependence on oxide thickness.

The "tunneling-assisted trapping" model, however, predicts a linear dependence of  $S_{IB}$  on the base current  $I_B$  [12][5]. This model assumes that the  $1/f$  noise results from the dynamic carrier trapping and detrapping processes when carriers are close to the spacer oxide covering the emitter-base junction. In the trapping model,  $S_{IB}$  can be expressed as:

$$S_{IB} = \frac{q^4 N_T \lambda}{k T A C_{sc}^2 f} \frac{I_{S0}^2}{I_{B0}} I_B \quad (2)$$

This trapping model also predicts that  $S_{IB}$  is inversely proportional to emitter periphery ( $P_E$ ), since the EB spacer surface region  $A$  is proportional to the emitter periphery. As can be seen in Figure 11, the pre-irradiated devices exhibit a clear  $1/A_E$  dependence, while the post-irradiated transistors deviate from this

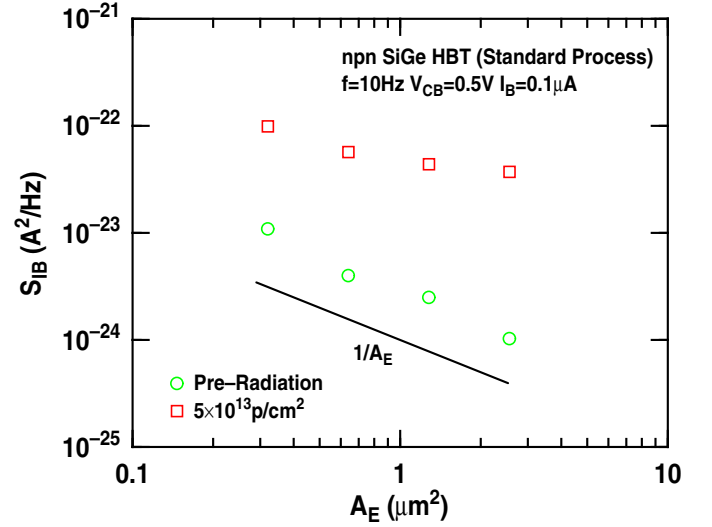


Fig. 11. Effects of irradiation on the geometrical dependence of hte npn and pnp SiGe HBTs.

behavior. More noise data on devices with differing P/A ratios will be required to clearly differentiate if this follows a  $1/P_E$  behavior, and is in progress.

The base bias current dependence, together with the apparent changes in the geometrical dependence of the noise data in response to ionizing radiation for the npn SiGe HBT, appears to be consistent with an evolution from the dominance of the fluctuation theory to the trapping theory as the dominant noise mechanism in these npn SiGe HBTs. Why this behavior is not seen in the pnp SiGe HBTs remains under investigation, although it is conceivable that the inherently higher noise magnitudes of the pnp devices compared to the npn devices simply "masks" the change in bias dependence with radiation exposure.

#### V. SUMMARY

We have presented the first radiation results of complementary SiGe HBTs, and used radiation to probe the differences in underlying physics of  $1/f$  noise between npn and pnp SiGe HBTs.

#### VI. ACKNOWLEDGEMENT

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